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TEST RESULTS FOR PROTOTYPE GPS RUBIDIUM CLOCKS

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ABSTRACT

This paper presents the results of a series of stability and qualification-level environmental and performance tests on two prototype rubidium frequency standards for the GPS navigation satellite program. One unit was subjected to a 140-day stability test at NBS and demonstrated a drift-corrected stability of $\sigma_y(\tau) = 2.8 \times 10^{-12}\,\tau^{-1/2} + 3.0 \times 10^{-16}\,\tau^{+1/2}$ for $1 \leq \tau \leq 10^6$ seconds, thus meeting the goal of [illegible] x 10^{-13} at 10^5 seconds. The average drift was -2×10^{-13}/day. The other unit was successfully subjected to a variety of performance and thermal, mechanical, EMI, and magnetic testing. It exhibited a smooth temperature coefficient of $-1 \times 10^{-13}/°C$. The test program and subsequent additional work have resulted in a better understanding of instability mechanisms and promise a stability below 1×10^{-13} out to 10^6 seconds.

INTRODUCTION

EG&G, Inc., has been engaged since early 1980 in a program to develop a Rubidium Frequency Standard (RFS) for the Global Positioning System (GPS). The design of the EG&G GPS RFS was described at this conference in 1981[1], and the basic concepts have changed very little since then. Subsequent work has resulted in the building and testing of two prototypes (see Figure 1).

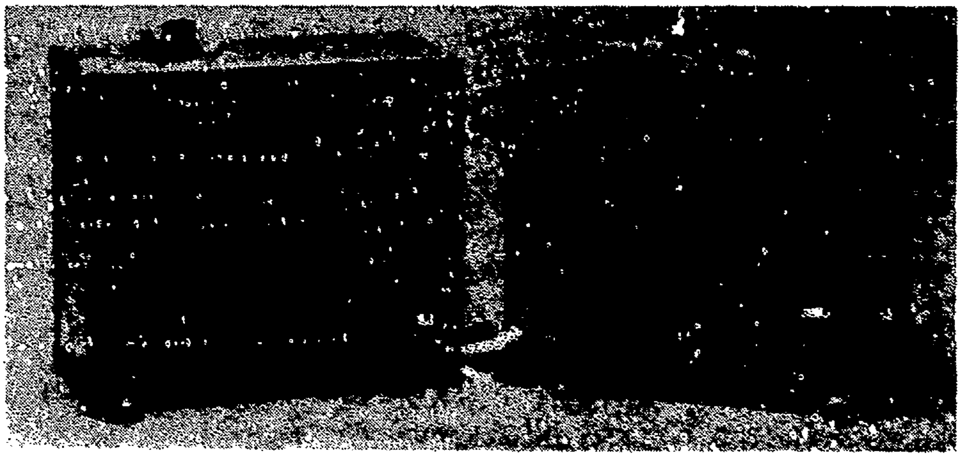

Figure 1. Photograph of EG&G GPS RFS Prototypes.

One unit was subjected to long-term stability testing over a 7½-month period without failure at the National Bureau of Standards (NBS). The other prototype was subjected to qualification levels of electromagnetic, mechanical, and thermal tests. That unit was then put on a stability test which accumulated over 7 months of failure-free operation. This paper summarizes results of those tests.

140-DAY STABILITY TEST

The primary objective of the 140-day stability test was to determine the Allan variance of the frequency scatter at averaging times between 10^5 and 10^6 seconds. Secondary objectives were to observe the phase and frequency records, to determine the stability at shorter averaging times, and to monitor the general behavior of the unit over an extended period of time.

This test was conducted at NBS between September 1982 and January 1983 in a specially built test setup that simulated the +35°C baseplate temperature and vacuum conditions that the unit would experience in operation on a GPS spacecraft. The test facility included a thermovac chamber, a fail-safe power system, monitoring equipment, and provisions for measuring RFS performance against the NBS clock ensemble. The frequency was adjusted to an absolute value of about -4.5×10^{-10} as required to compensate for the in-orbit gravitational red shift.

The RFS ran normally throughout the test and did not exhibit any performance degradation.

The frequency record is shown in Figure 2 and the residuals after subtraction of the linear least-squares drift of -2×10^{-13}/day are shown in Figure 3. This drift was twice the specified value of $\pm 1 \times 10^{-13}$/day but was smooth and highly modelable, and thus was not a severe problem for the GPS application. (The current GPS rubidium clocks have a drift specification of $\pm 1 \times 10^{-12}$/day.) Furthermore, subsequent testing on Prototype No. 2 has identified a probable dominant cause of drift that, when eliminated, should result in a significant improvement in this parameter. The most prominent features of the residuals are occasional jumps of about $+5 \times 10^{-13}$. These are the primary limitations on the modeled long-term clock performance and were apparently related to jumps of about -0.25% in the rubidium lamp output.

This unit had a lamp with a heavy rubidium fill (474 µgrams) as compared with a normal fill of 70-100 µgrams which is adequate for a life greater than the specified 7.5 years. It is believed that the heavy lamp fill is responsible for the jumps. No such behavior has been observed in the other unit, which has a lamp with a normal rubidium fill. Both units were tested with the lamp tip upward, so there were opposing thermal and gravitational forces acting on the molten rubidium.

The scatter of the drift-corrected frequency fluctuations is shown on the Allan variance plot of Figure 4. The measured results lie well below the specification limits shown by the dashed line and meet the goal of 1×10^{-13} at 10^5 seconds. The unit displays a $2.8 \times 10^{-12}\ \tau^{-\frac{1}{2}}$ white frequency noise characteristic in the region below about 10^4 seconds (corrected for the reference noise) that is in good agreement with theoretical predictions[1]. At longer averaging times, the plot shows a random-walk frequency characteristic at a level of about $3.0 \times 10^{-16}\ \tau^{+\frac{1}{2}}$. There is no significant region of flicker frequency noise. During those intervals when no jumps occurred, the drift-corrected Allan variance was about 5×10^{-14} at 10^5 seconds.

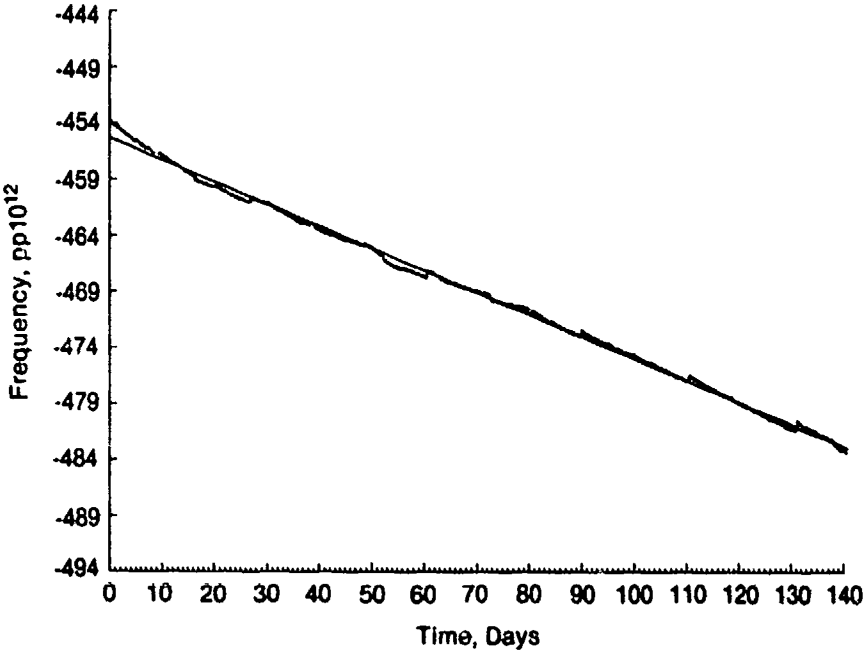

Figure 2. Tau = 2-hour frequency record versus NBS clock ensemble 9/6/82-1/25/83, EG&G GPS RFS Prototype No. 1.

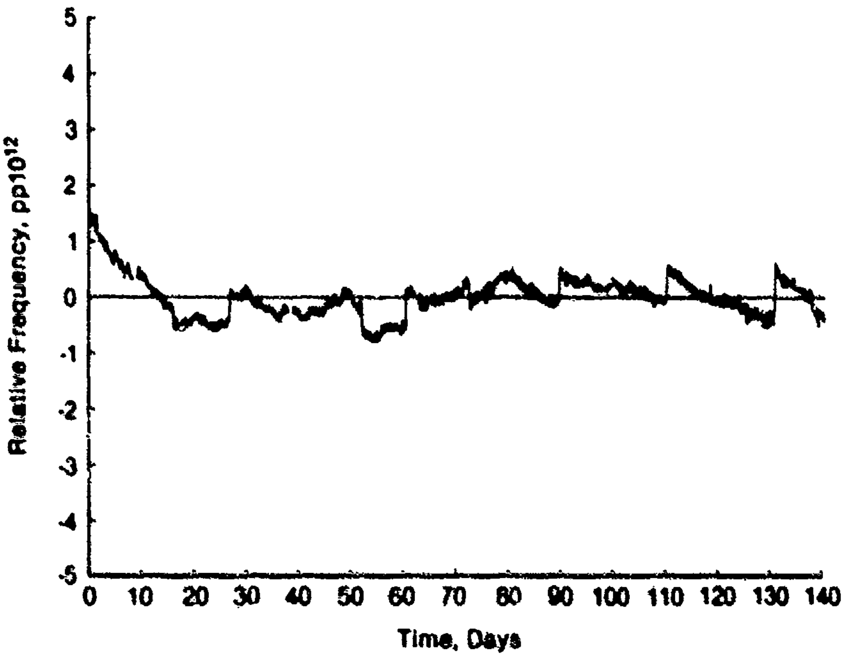

Figure 3. Tau = 2-hour residuals versus NBS clock ensemble after drift correction, EG&G GPS RFS Prototype No. 1.

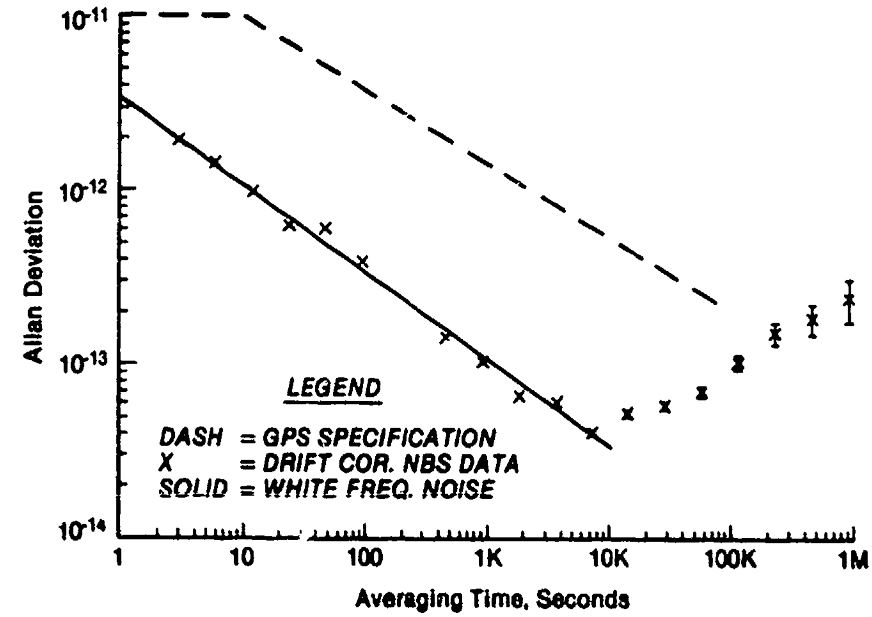

Figure 4. Time-domain frequency stability measured at NBS 9/6/82-1/25/83, EG&G GPS RFS Prototype No. 1.

The subtraction of a least-squares linear frequency drift tends to filter out long-term fluctuations and thus give an overly optimistic result at long averaging times. Nevertheless, the results of an ARIMA maximum likelihood estimate of stability made by NBS are essentially the same as the drift-corrected Allan variance values out to about 3 x 10^5 seconds.[2] These data are shown in Figure 5.

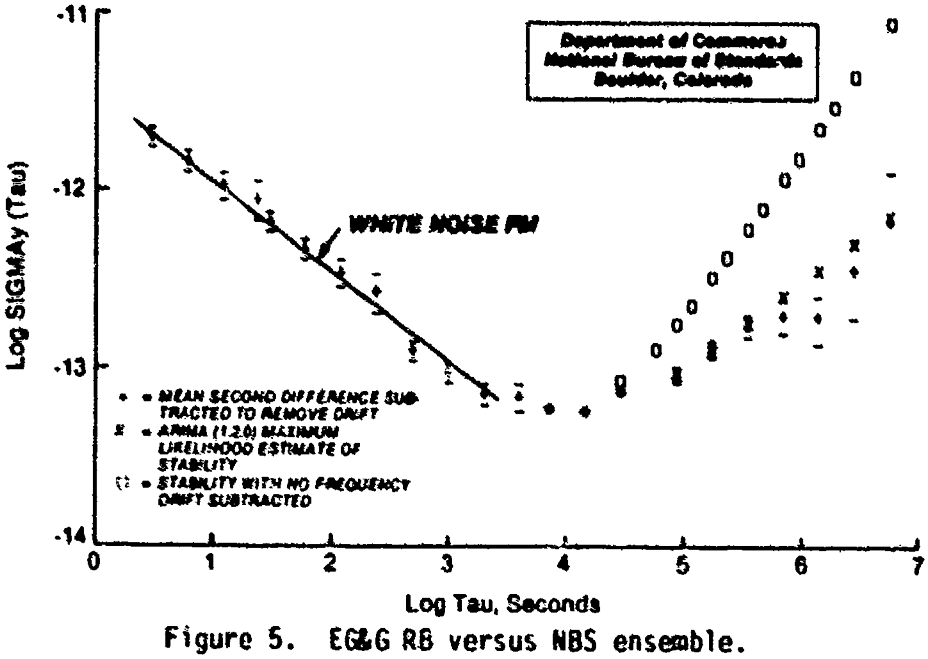

Figure 5. EG&G RB versus NBS ensemble.

ADDITIONAL STABILITY TESTS

In addition to the 140-day stability test, shorter runs were made between January and April 1983 at maximum and minimum C-field and a restart test was done. The C-field value did not have any significant influence on the RFS stability. The unit showed a frequency offset of about $+3 \times 10^{-12}$ when restarted after a 3-day shutdown.

Stability tests were also conducted on Prototype No. 2 at EG&G after qual-level testing. Typical of the excellent results are Figure 6 which shows a drift well below 1×10^{-13}/day and Figure 7 which shows a scatter below 3×10^{-14} at 10^5 seconds. The stability at the shorter averaging times is limited by the cesium reference (HP 5061A Opt. 004). No frequency jumps were observed over a 7-month test period.

QUALIFICATION-LEVEL TESTS

Qualification-level testing was performed on EG&G GPS RFS Prototype No. 2 during the period between October 1982 and March 1983. The primary objectives were to discover and correct design deficiencies. The test conditions were as specified for formal qualification, but the terminology "qual level" was used because the test unit was built as a prototype, rather than with high reliability parts and strict quality control.

Many of the tests were conducted more than once, as retests to verify corrective actions to the test unit or because of deficiencies in the initial test equipment or procedure.

Certification Tests

Testing of Prototype No. 2 began with a series of expanded certification tests intended to establish the general performance of the unit. Besides the standard functional tests conducted after each test sequence (frequency accuracy, dc power, and rf output power and harmonics), tests were performed for phase noise, backup tuning, primary tuning, frequency versus input voltage, frequency stability at fixed temperature, and frequency versus normal operating temperature. Most of these tests, as well as the above stability tests, were performed in vacuum to simulate the GPS environment, to produce effects such as component temperature increase due to loss of convective cooling, and to provide the vacuum insulation for which the physics package design is optimized.

No serious difficulties were experienced. The only discrepancies were associated with the secondary loop OCVCXO. The unit had insufficient varactor tuning range (-0.9 to $+1.8 \times 10^{-7}$ versus the specified $\pm 2 \times 10^{-7}$) and could not maintain lock above about +40°C (versus the specified +60°C). These problems are expected to be corrected in the next unit.

The RFS easily met its phase noise, primary tuning range, and voltage coefficient requirements. The measured voltage coefficient was -8×10^{-14}/V. The stability test gave a 10^5 seconds Allan variance of 1×10^{-13}, a final drift rate below 1×10^{-13}/day, and a TC of -1×10^{-13}/°C. These results show that the RFS prototype is capable of excellent stability.

The average TC of -1×10^{-13}/°C over the normal operating temperature range of +20 to +45°C was confirmed to be smooth and was x10 lower than the specification limit. The RFS is free of any region of large incremental temperature sensitivity. This was

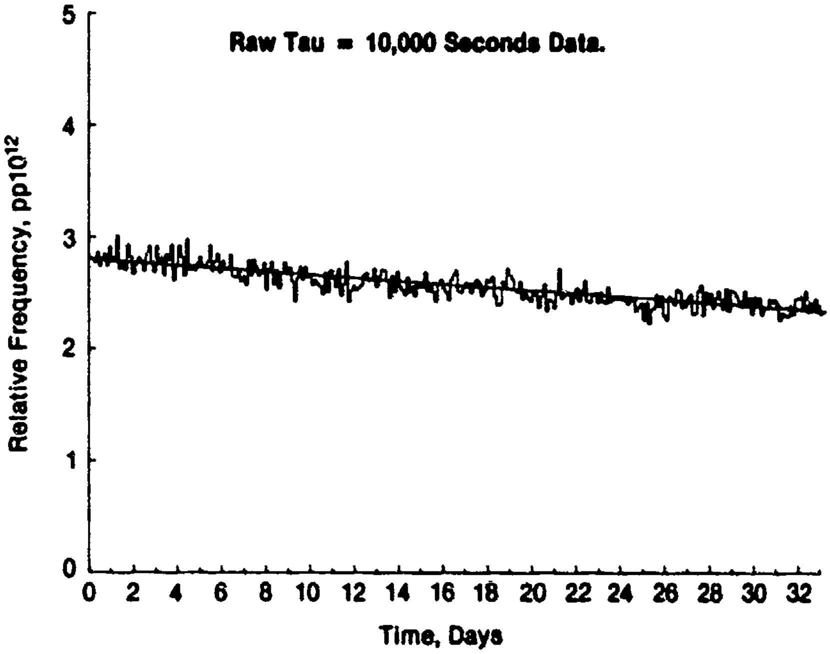

Figure 6. EG&G GPS RFS Prototype No. 2 stability test, 6/16/83-7/19/83.

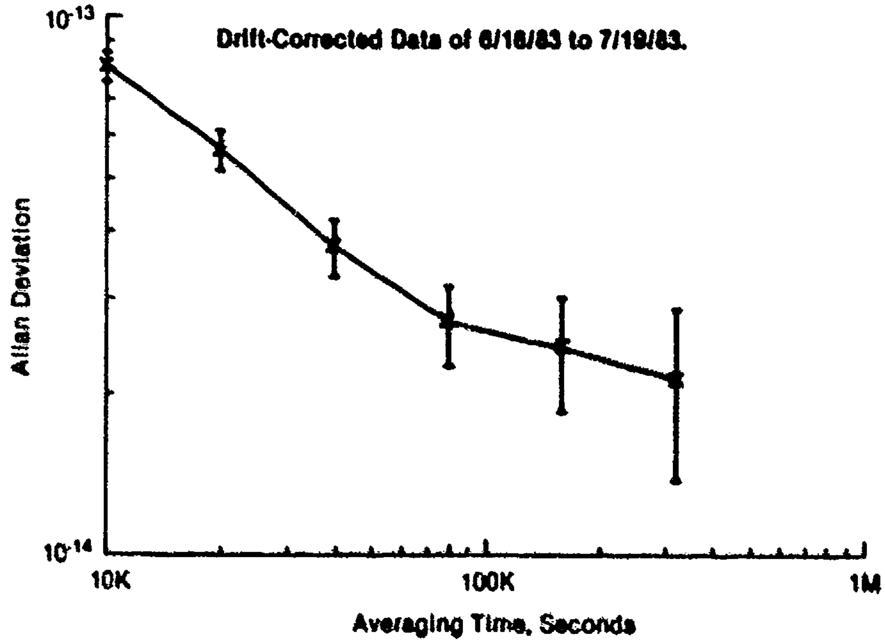

Figure 7. Time-domain stability of EG&G GPS RFS Prototype No. 2.

confirmed by observing the frequency record while varying the baseplate temperature from 20°C to 45°C to 20°C in 1°C steps. One hour was allowed for each step with 8 hours at 45°C. The results are shown in Figure 8. The scatter in the data is determined primarily by the stability of the cesium reference.

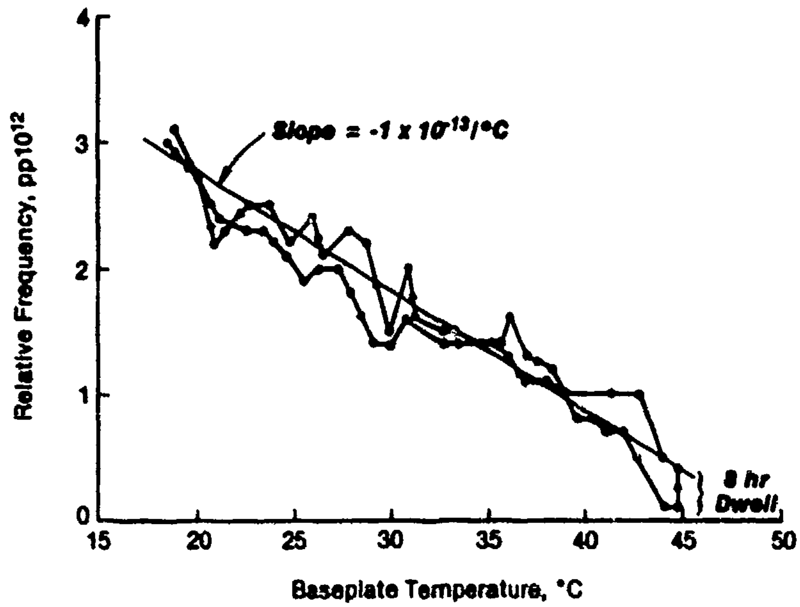

Figure 8. Frequency versus temperature.

EMI Tests

EMI testing proceeded quite well, and, although several deficiencies were found, most are felt to result from the use of improper cabling and cable terminations. During testing, several problems were improved greatly by altering cable terminations. These tests showed the importance of utilizing the exact cables and terminations to be used in flight and also the need to simulate the space vehicle power supply. Input ripple measurements are dependent on the characteristics of the supply.

There was no conducted susceptibility at the critical servo modulation frequencies. This is usually the most difficult aspect of an RFS under exposure to EMI, and therefore the result was most encouraging. An audio frequency power line susceptibility was associated with the +5V portion of the switching power supply and its effect on the synthesizer phase detector was corrected by the addition of a regulator.

The only other susceptibility of real concern occurred as a result of monitor cable pickup at the primary loop frequencies and a few frequencies related to the cable length. It is unclear whether any change is required in the RFS, since a better cable may eliminate the problem.

The few excessive radiated emissions were also associated with the monitor cable and its grounding and termination. An excessive power supply conducted ripple was observed and corrected.

Additional testing will be required with improved cables to determine if other improvements are needed.

Temperature Cycling Tests

Temperature cycling between +50°C and -30°C was performed at 1 atmosphere (dry nitrogen) and in vacuum. At each temperature extreme, the RFS was turned off, then restarted after 30 minutes.

The purpose of these tests was to establish proper RFS startup and operation, although performance requirements did not apply over this temperature range. The results were satisfactory except that secondary oscillator unlock occurred at the high end. This resulted from use of a crystal having too low a turnover temperature and has been corrected.

Because the 30-minute Off time was not sufficient for the RFS (in particular, the ovenized crystal in the secondary oscillator) to stabilize at low temperature, an additional test was performed. The RFS, unpowered, soaked overnight at -19°C in vacuum, was restarted, and warmed up within 1 hour.

Vibration Tests

The qualification random vibration spectrum had a peak level of 0.35 g^2/Hz from 120 to 500 Hz and an overall level of 17 g rms from 20 to 2000 Hz . The duration was 3 minutes per axis. The RFS was powered and monitored during vibration. In service, the RFS would not be operating during (launch) vibration. It was powered and monitored during testing to detect failures such as intermittents, not to verify performance. The shaker magnetic field and its effects on the RFS were evaluated and made acceptable by modifying the setup.

RFS Prototype No. 2 was subjected to vibration testing on four occasions. Failures, with the exception of the secondary oscillator, were corrected by minor changes as described below and the vibration test passed. In the final testing, a laboratory synthesizer functionally replaced the secondary oscillator, which had no output. During vibration, loss of primary and secondary loop lock occurred, but lock was recovered after vibration and thus is not considered a failure.

Most of the failures which occurred during the first tests were associated with mounting of electronic components, such as fracture of leads and solder joints. The corrective action was to bond heavier components to the printed circuit boards with epoxy.

A number of threaded fasteners came loose. The corrective action was to lock the threads by applying Solithane 113/300 urethane coating at assembly (split lock washers and Loctite are prohibited).

A problem was encountered where the center conductor in a connector on flexible coaxial cable withdrew into the connector due to flexing of the cable from vibration or handling. The connector was changed to a design which has mechanical support behind the center contact.

A diode failure (fracturing of the glass body) occurred on a printed circuit board which had been subjected to an uncontrolled mechanical shock due to test equipment malfunction before the start of the qualification-level test program. A new board with five diodes passed qual vibration.

The secondary oscillator had two failures during vibration testing. The first was a change in frequency which was reset by the supplier. The second failure was a loss of output. It was determined by the supplier that the crystal had broken. The crystal was replaced and reportedly the oscillator was subjected by the vendor to the qual vibration level and passed.

Magnetic Susceptibility

The RFS contains three magnetic shields that reduce its susceptibility to frequency changes caused by external magnetic fields. At maximum internal C-field (250 mG), the physics package has a worst-case magnetic sensitivity of 4.2×10^{-8}/G along the optical axis. This requires an overall shielding factor of 126,000 to meet the magnetic susceptibility requirement of 1×10^{-12}/3 gauss.

Shielding factor measurements were made using Model 124A EG&G lock-in amplifier, a Model DH-200 audio power amplifier, a custom made pick-up coil the size of the absorption cell, and a Helmholtz coil. A frequency of 23 Hz with an amplitude of 8 V rms (6 gauss peak to peak) was used to drive the Helmholtz coil. With all three shields hydrogen annealed and nested and the pick-up coil in the same location as the absorption cell, a shielding factor over 200,000 was measured.

Shielding factors were also measured during assembly of the physics package in order to determine if and when any degradation of its two shields occurred due to rework and assembly operations. No significant changes were measured. The two nested cylindrical shields had a shielding factor of 11,400 initially and 10,400 after assembly.

An overall magnetic susceptibility test was conducted on RFS Prototype No. 2. As expected from the shielding factor measurements, the overall results were excellent. Under worst case conditions of maximum internal C-field and orientation of the external field along the physics package optical axis, the magnetic susceptibility was 1×10^{-12}/6 gauss (reversal of a 3-gauss field) or 2×10^{-13}/gauss. This is at least 2:1 better than specified and the actual susceptibility is probably even less, since the measurement resolution is limited by the stability of the reference and the unit under test.

Acceleration Test

RFS Prototype No. 2, with the secondary oscillator replaced by a dummy load, was subjected to acceleration of 20 g for 5 minutes in each direction of three mutually perpendicular axes (total of 6 runs) using a centrifuge with a 4-foot radius. During exposure, the RFS was powered and the input current was monitored. Between exposures, complete sets of monitor readings were taken.

A slight increase in input current was observed during acceleration. After acceleration in the +Z direction, there was an increase in the light and signal, apparently due to movement of (molten) rubidium from the back of the lamp onto the hotter surfaces. This condition did not result in any malfunction and was partially reversed by subsequent acceleration in the opposite (-Z) direction and was fully corrected by overnight operation.

The RFS showed normal frequency and frequency stability after the test.

Shock Test

RFS Prototype No. 2, with the secondary oscillator replaced by a dummy load, was subjected to three pyro shocks in each of three axes (both directions excited by each shock). The shock spectrum extended from 100 to 10,000 Hz with a peak value of 1250 g from 1250 to 3200 Hz. An electrodynamic shaker and shock synthesizer were used. During exposure, the RFS was not powered. Monitor readings were taken between axes, during which an intermittent short circuit was discovered. The cause was contact between the lamp oscillator enclosure and the main chassis due to a misalignment in the physics package mounting. This was corrected by inserting a strip of insulation between the enclosure and the chassis. After subsequent shock testing, monitor readings were normal.

Conclusions Obtained from Qualification-Level Tests

The qualification level testing of RFS Prototype No. 2 indicates that this design is capable of meeting the GPS requirements. Most of the failures were minor and were easily corrected. They reflected that the test unit was a prototype, not initially constructed as a qualification unit with strict quality control. The only major failure was with the secondary oscillator, which also was an engineering model not initially constructed for qualification testing. Corrective actions to the oscillator have been implemented and have reportedly been verified by the vendor. The packaging design of the RFS, which provided easy access for initial assembly, also facilitated troubleshooting and rework.

DEVELOPMENT TESTS

Besides the stability and qual level testing of the RFS prototypes, a significant amount of other testing was performed on various assemblies. The purpose was to obtain empirical design data, to measure performance, and/or to verify reliability. A brief list of the more important tests follows:

1. Lamp aging with measurements of rubidium consumption by calorimetry.

2. Measurements of thermal contact resistances in vacuum for heat sinks and bolted joints, including PC board mounting.

3. Temperature cycling of potted thermistors with measurements of dissipation constants, coaxial cable assemblies with X-rays, and the large area photodetector assembly (manufactured in house).

4. Measurements of oven temperature stability, thermal gain of oven temperature controllers, and thermal time constants of ovens, heaters, and thermistors.

5. Measurements of magnetic field uniformity in C-field coils of various configurations.

6. Magnetic shielding factor measurements of nested shields with various end gaps.

7. Vibration testing of lamps to investigate the displacement of (molten) rubidium.

8. Thermal profile of the RFS: measurement of temperatures in vacuum to verify that component junction temperatures do not exceed 125°C.

CONCLUSIONS

This paper has presented test results on two prototype rubidium frequency standards that are among the best such devices yet reported. A summary of their characteristics is shown in Table 1. They have demonstrated excellent stability and reliability when operated many months under GPS thermovac conditions. They showed low sensitivity to environmental factors such as temperature, magnetic field, and supply voltage, and they are capable of meeting the GPS environmental requirements of shock, vibration, acceleration, and temperature cycling. This has been accomplished by careful attention to all aspects of classical RFS design. It has been satisfying to see how successfully the size, weight, power, and signal-to-noise advantages of rubidium clock technology could be combined with low physics package parametric sensitivites and other design details to achieve excellent overall performance.

Table 1. Characteristics of EG&G GPS RFS.

Size:	4.46" X 8.36" X 6.89" high
Weight:	10 lb.
Power:	13 watts (at +35°C baseplate in vacuum)
Operating Temperature Range:	+20 to +45°C
Drift:	$\pm 1 \times 10^{-13}$/day (spec)
Stability:	$2.8 \times 10^{-12}\ \tau^{-\frac{1}{2}} + 3.0 \times 10^{-16}\ \tau^{+\frac{1}{2}}$
	(typical $\sigma y\ (\tau)$ for $1 \leq \tau \leq 10^5$ sec)
Temperature Coefficient:	-1×10^{-13}/°C (typical)
Magnetic Susceptibility:	2×10^{-13}/gauss (typical)
MTBF:	178,000 hours (calculated)

ACKNOWLEDGMENTS

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The authors wish to acknowledge the excellent manner in which the National Bureau of Standards Time and Frequency Division staff set up, conducted, and analyzed the results of the long-term stability test.

Many persons contributed to the success of this effort at EG&G. In particular, P. Labrecque and K. Lyon were deeply involved in the qualification-level testing and S. Goldberg provided overall scientific direction of the program.

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1. W.J. Riley, "A Rubidium Clock for GPS," Proceedings of the 13th Precise Time and Time Interval (PTTI) Applications and Planning Meeting, pp. 609-630, December 1981.

2. "Final Report for 140-Day Stability Test of GPS Rubidium Frequency Prototype," NBS Test No. 801590, Time and Frequency Division, National Bureau of Standards, Boulder, Colorado 80303.

QUESTIONS AND ANSWERS

MR. WARD:

Sam Ward, J.P.L. How about the projected life between cesium and the rubidium?

MR. RILEY:

Well, earlier rubidium had lamp problems. That is why we emphasize this lamp problem, but we believe we have it licked. Cesium seems to have a finite life, depending on the design. Myself, being very prejudiced, I would guess that the rubidium could be extended out over a longer period of time than the cesium, but that is a very prejudiced point of view.

A VOICE:

Some of your competitors are indicating 25 years life for rubidium standards, can you comment on that?

MR. RILEY:

The unit I'm describing is twenty years. That's almost entirely an electronic number. Twenty years on the lamp does not frighten us; twenty years on the other cells would frighten us even less.

A VOICE:

What is going into the present, the new birds rubidium, cesium or a combination?

MR. RILEY:

It's a fifty-fifty mix, I understand; two each, and not one of this design. We have gotten to the prototype stage, and that's as far as the new design has been taken.